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Extruded Fiber Reinforced Cement Pressure Pipe

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Extrusion is a plastic-forming method that is suitable not only for flat shapes, but also for structural shapes, such as I-sections, channels, pipes, and hollow and solid tubes. The advantage of introducing extrusion into cement product processing is that the materials are formed under high shear and compressive forces resulting in composites with improved performance. This article presents research results on extruded fiber reinforced cement pipe and flat sheet. A pipe die was designed and developed specifically for extrusion of cement based materials. Three different mix proportions were selected by varying the fiber type (polyvinyl alcohol and alkali-resistant glass), admixture type (silica fume, metakaolin, and latex), and their proportions to study their influence on the properties of extruded fiber reinforced cement pipes and thin sheets. Extruded cement pipes were tested for hydrostatic burst strength, bearing strength, and flexural performance. Thin sheets were tested for tensile and flexural performance. The test results indicated that polyvinyl alcohol fibers in the presence of silica fume and latex provide a suitable reinforcing effect, and silica sand provides good surface finish. Advanced Cement Based Materials 1998, 8, 47–55. *© 1998 Elsevier Science Ltd.*

KEY WORDS: Bearing, Burst, Cement, Composite, Deflection, Extrusion, Fibers, Flexure, Hydrostatic, Latex, Metakaolin, Modulus of elasticity, Pressure, Silica fume, Silica sand, Strain, Strength, Tension, Toughness

The strength and toughness of cement matrix composite incorporated with continuous aligned fibers or mats increase by orders of magnitude [1–3]. Recent advances in processing techniques to incorporate short discontinuous fibers in cement matrix composites have led to the emergence of a new breed of high performance composites [4]. The performances of these composites are comparable to that obtained with continuous aligned fibers or mats.

The research group at Northwestern University has been working on developing extrusion technology to incorporate short fibers into the cementitious matrix. Extrusion is a plastic-forming process that consists of forcing a highly viscous, dough-like plastic mixture through a shaped die. The process is continuous and simpler to use than other conventional methods, making it most suitable for industrial production. The advantage of extrusion is that it is an economical mass-production method capable of producing not only flat shapes, but also structural shapes. Extrusion technology is a potential candidate for low cost commercial applications, among which are pressure pipes. One needs to control the rheology of uncured cementitious paste to successfully accomplish processing. Techniques and organic and inorganic additives are needed to modify the rheology. The advantage of introducing extrusion into cement product processing is that the materials are formed under high shear and high compressive forces. With this technology tensile and bending strength comparable to those achieved by continuous fiber technology have been achieved.

Previous research at Northwestern University has shown that using polyvinyl alcohol fibers sheets can be extruded which exhibit both the increased tensile strength and strain-hardening type of response [4]. Improved performance of extruded fiber reinforced cement (FRC) sheets prompted us to extrude pipes and test them for hydrostatic burst strength, bearing strength, and flexural performance. Thus, without any conventional reinforcement, fibers provide reinforcing effect to improve the material properties of pipes for hydrostatic pressure.

This article presents a research investigation on refinement of the mixture proportions and manufacturing technique to extrude pipes with improved performance and surface finish. While pipes were tested for hydrostatic burst strength, bearing strength, and flexural performance, thin sheets were tested for tensile and flexural performance.

Experimental Program

Mix Proportions and Manufacture

Three mix compositions were selected for this investigation. Table 1 presents details of mix ingredients and

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TABLE 1. Details of test series and mix proportions

	Test Series					
	MIX_1		MIX_2		MIX_3	
Mix Ingredients	(%)	(g)	(%)	(g)	(%)	(g)
Cement		6000		6000		6000
Silica fume (slurry)	30	3600	30	3600	—	—
Metakaolin	—	—	—	—	20	1200
Silica sand	25	1500	25	1500	25	1500
Water added	28	805	28	90	40	1780
Latex (suspension)	—	—	21	2500	21	2500
Methyl cellulose	1	60	1	60	1	60
HRWR (suspension)	4	240	1	60	1	60
PVA fibers (% by volume)	3	195	3	210	—	—
Glass fibers (% by volume)	—	—	—	—	3	410

Note: The amounts of silica fume, latex, and HRWR presented in the table contain 50%, 52%, and 60% water by weight, respectively.

their proportions. The variable in test series included: (a) MIX_1, containing silica fume and polyvinyl alcohol (PVA) fibers (water to binder ratio 0.352); (b) MIX_2, containing silica fume, latex (styrene butadiene), and PVA fibers (water to binder ratio 0.357); and (c) MIX_3, containing metakaolin, latex, and glass fibers (water to binder ratio 0.371). All the mix compositions had 3% fibers by volume. Latex and silica sand were selected to improve the toughness of the composite, as well as surface finish. Metakaolin was selected for test series containing glass fibers in MIX_3 since it has been found to improve the long-term durability of glass fiber reinforced cement (GFRC) composites [5,6].

Manufacture of fiber reinforced cementitious composites by extrusion is similar to other processes for cement based materials, except that one step is added to extrude the material, while avoiding two steps: molding and demolding. The manufacturing process includes premixing, extrusion, and curing. Conventional pipe die used in ceramic and plastic extrusion could not be used for fiber reinforced cement extrusion. Stiffness of cement matrix and fibers resulted in defects at re-knitting points (i.e., where the inner die is connected to the outer die). A new die was designed and developed, which consists of a free rotating inner die connected to an auger shaft with the help of two universal joints. The stiffness of the mix and the pressure keep the inner die firmly at the center of the outer die.

The composite batches were mixed in a regular high shear mortar mixer. First silica fume (Force 10,000D, W.R. Grace & Co.), in MIX_1 and MIX_2, or metakaolin (Englehard Metamax) in MIX_3, silica sand (Grade F-85, U.S. Silica), and fibers (Kuraray International, length = 6 mm, diameter = 14 μm) were mixed for about 2 minutes or until all the fibers are separated and well-coated. Silica fume or metakaolin was used for two reasons: as packing filler and dispersion of fibers. Then cement, predispersed with a processing aid, hydroxypropyl methylcellulose (METHOCEL, Dow Chemical Company), was gradually added to the mixer along with water and high range water reducer (WRDA-19, W.R. Grace & Co.). High range water reducer (HRWR) was used to wet the particles and to improve the workability of the mix with the minimum water content. Mixing was continued for 5 more minutes or until a dough-like consistency was achieved. Premixing is necessary for composite extrusion to achieve uniformly dispersed particles and fibers in the mix.

The premixed material was then transferred into the pug mill chamber of the extruder. An auger extruder (Starkey Model 990H-1, 3 HP motor, supplied by Starkey Machinery, Inc., Galion, Ohio, USA) was used in this investigation. The auger extruder provides continuous processing and is commonly used in the industry. The premixed materials further get mixed in the chamber and de-aired before being pushed through the die. The pipe, once it comes out of the die orifice, was extruded over a Teflon tube, which acted as a support to retain shape until the composite achieved enough strength (24 hours) (Figure 1). Lubricant (WD-40) was sprayed on the surface of the Teflon tube to reduce surface friction between the Teflon tube and the extruded material. The pipes were then demolded by shrinking the inner Teflon tube with the help of ice and cured at 20°C and 100% relative humidity (RH), until the age for testing. All the specimens were tested at 28 days' age. A minimum of two specimens 203.2 mm (8 inch) or 304.8 mm (12 inch) were used for each test. A good extruded pipe should present characteristics comparable to that of extruded sheet. To quantify the performance of the pipe for burst strength, plate specimens were also extruded and tested for tensile and flexural performance. All the results presented in the tables represent average values.

Pressure Test

Hydrostatic pressure/burst test was performed according to ASTM C-500 [7], the test set-up for hydrostatic pressure/burst strength of pipe is shown in Figure 2. The pipe specimen used for this test was 304.8 mm (12 inch) long, 6.35 mm (0.25 inch) thick, and about 76.2 mm (3 inch) in diameter. The open end of the pipe was connected to specially made aluminum fixture. Water tightness was achieved with the help of O-rings inserted between the aluminum fixture and the pipe. The pipe was then filled with water (making sure to eliminate air bubbles inside) and the valves closed. It was then connected to a nitrogen source to apply pressure. The pressure was then gradually increased and the

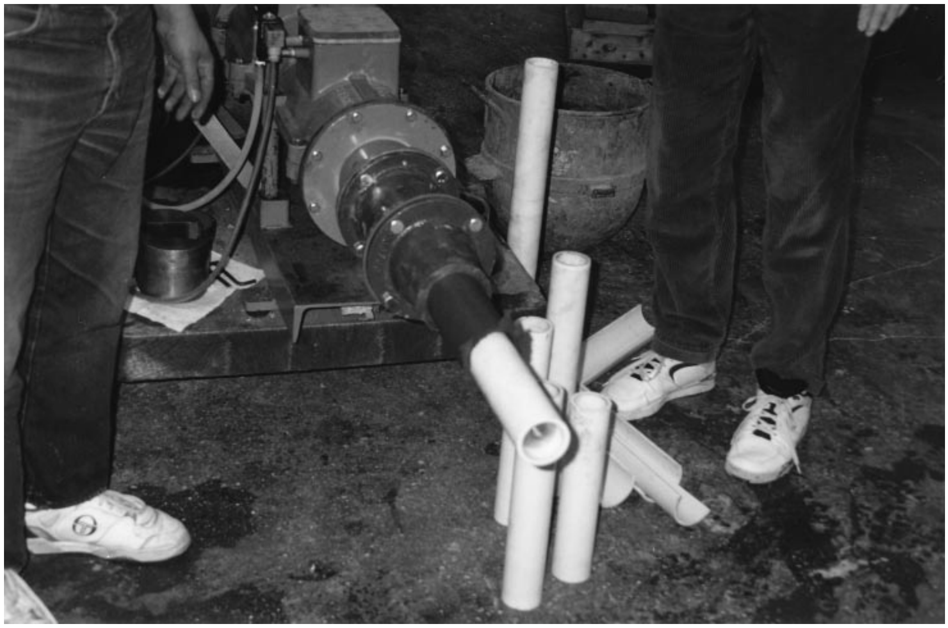

FIGURE 1. Extrusion manufacturing process for FRC pipes.

readings were recorded with the help of a gauge. The pressure sufficient to burst (when first crack was observed) the specimen was then recorded. The cracks were directed along the generating lines of the pipe. Two specimens were tested for each test series.

Bearing Test

Bearing test (V-shaped three-edge bearing) was performed according to ASTM C-500 [7]. The test set-up for bearing test is shown in Figure 3. The pipe specimen used for this test was 304.8 mm (12 inch) long, 6.35 mm (0.25 inch) thick, and about 7.62 mm (3 inch) in diameter. The test was performed using a computer-controlled closed-loop hydraulic testing machine. Two specimens were tested for each test series.

Flexural Tests

FLEXURAL TEST FOR PIPES. Flexural test for pipe was performed according to ASTM C-500 [7]. The test set-up for flexure of pipe is shown in Figure 4. The pipe specimen tested for flexural strength was 254.0 mm (10 inch) long, 6.35 mm (0.25 inch) thick, and about 76.2 mm (3 inch) in diameter, and was subjected to four-point loading (span of 203.2 mm, 8 inch). The test was performed using a computer-controlled closed-loop hydraulic testing machine. Besides measuring load-point deflection, bottom deflection at the center of the specimen was also measured. One specimen for each MIX_1 and MIX_2 was tested.

FLEXURAL TEST FOR SHEETS. The flexural test for sheet was performed according to ASTM C-947 [8]. The test set-up for flexure of sheet specimen is shown in Figure 5. The sheet specimen tested for flexural strength was 203.2 mm (8 inch) long, about 25.4 mm (1 inch) deep, and 5.08 mm (0.20 inch) wide. A digital closed-loop hydraulic testing machine was used for flexural tests. The load-point deflection was used as a feed-back signal to accurately obtain the load-deflection behavior. The dimension of the specimen was measured and was used in all the calculations. Three specimens were tested for each test series.

The bend-over point (BOP) corresponds to the point where the linearity of the load deflection curve changes. Stress and strain corresponding to the limit of proportionality (LOP) and failure (MOR) were calculated according to the ASTM C-947 [8] and European Standard [9]. The modulus of elasticity in flexure was calculated based on the deflection and the load values at the bend-over point. The toughness of the specimen was obtained based on the area under the load deflection curve up to the point where the post-peak load reaches 5% of the maximum load.

Tensile Tests

The test set-up for tension of sheets is shown in Figure 6. The extruded sheets were cut into specimens to accommodate in the loading grip of the direct tension testing machine. The sheet specimen tested for tensile strength was 203.2 mm (8 inch) long, about 25.4 mm (1 inch) deep, and 5.08 mm (0.20 inch) wide. The ends of the specimen were mounted with thin steel plates glued with epoxy resin on either side to make them stronger

FIGURE 2. Test set-up for hydrostatic pressure/burst strength of pipe.

to avoid any damage due to the grips and to assure that failure happened within the 76.2 mm (3 inch) long gauge length. A digital closed-loop hydraulic testing machine was used for tensile tests. Tensile strains were measured by two linear variable displacement transducers (LVDT) with a gauge length of 76.2 mm (3 inch). The average displacement was used for feed-back control. The dimension of the specimen was measured and was used in all the calculations. Three specimens were tested for each test series.

The modulus of elasticity in tension was calculated based on the stress strain curve up to one third of the maximum load point.

Results and Discussion

Hydrostatic Burst Strength

Figure 7 and Table 2 present hydrostatic burst strengths for different extruded FRC composites. The pressure was increased until the cracks formed and the pipe started leaking. The cracks were always directed along the generating lines of the pipes. An overall look at the graphs indicates that performance in hydrostatic burst strength for FRC extruded pipes containing silica fume and PVA fibers with or without latex is comparable and much better than that of FRC pipes containing metakaolin and glass fibers. However, MIX_2 performs better than MIX_1 and corresponding pressure is slightly higher (7%). MIX_3 shows much lower pressure: 44% and 41%, respectively, compared to MIX_1 and MIX_2. This might be explained by the higher dimensional variability. Be-

FIGURE 3. Test set-up for V-shaped three-edge bearing strength of pipe and typical crack pattern at failure.

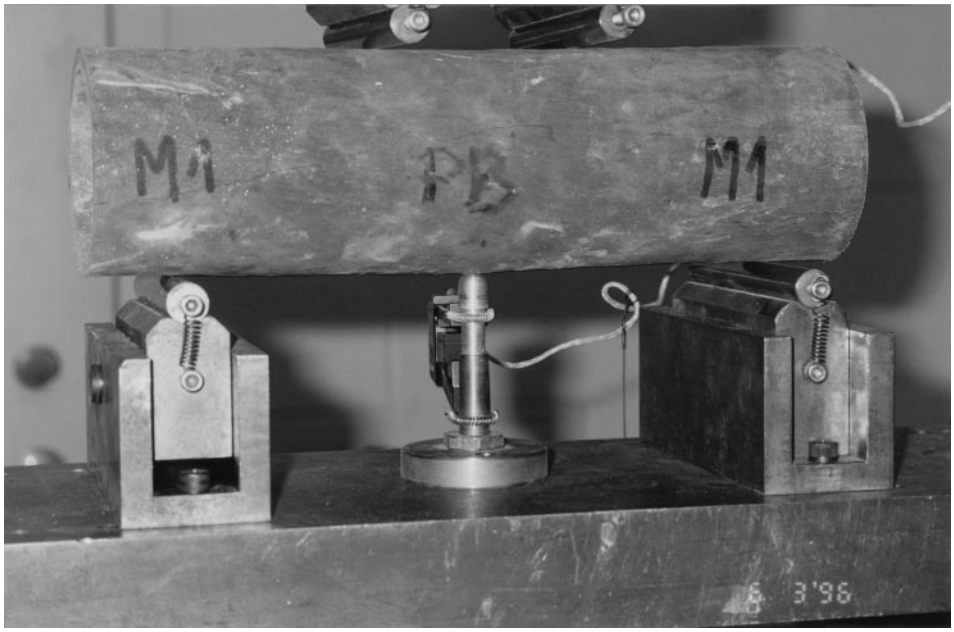

FIGURE 4. Test set-up for flexural strength of pipe and typical pipe failure.

cause of the technological process, the shape of the pipe is not perfectly circular, and both external diameter and wall thickness are not constant (variation in pipe thickness is up to 26% for MIX_1, 16% for MIX_2, and 60% for MIX_3. Among the mix compositions considered, MIX_3 shows the highest variation in pipe thickness.

Bearing Strength

Figure 8 and Table 2 present behavior of different extruded FRC pipes in bearing tests. An overall look at the graphs indicates that performance in bearing strength of FRC pipes containing silica fume and PVA fibers is much better than that of FRC pipes containing metakaolin and glass fibers. MIX_1 performs better than MIX_2 and its bearing strength is 19% higher. However, Figure 8 shows that MIX_2 has a more ductile behavior than MIX_1 in bearing. MIX_3 has a poor behavior in bearing and its bearing strength is 53% lower than that of MIX_1.

The pipe is a thin shell, with a thickness-to-external

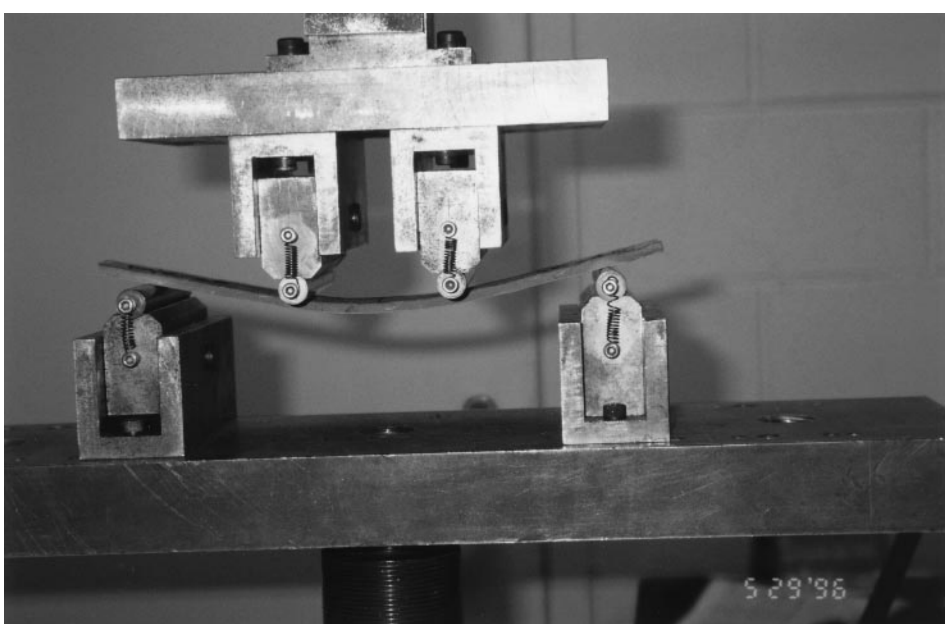

FIGURE 5. Test set-up for flexural strength of sheet and typical composite flexibility.

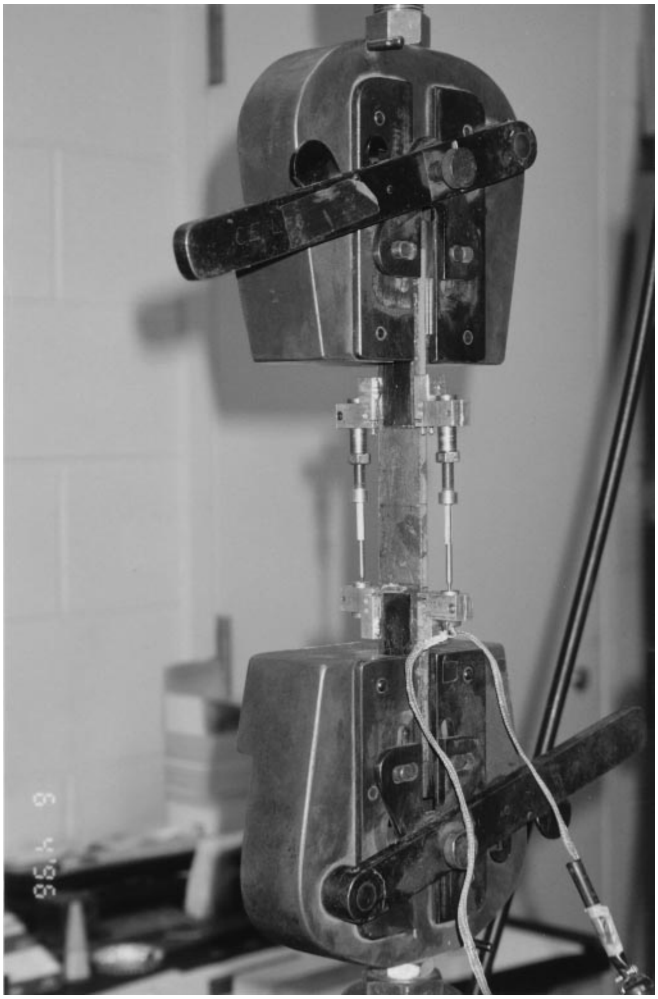

FIGURE 6. Test set-up for tensile strength of sheet.

TABLE 2. Test results of extruded FRC pipes

Test Series	Pressure (MPa)	Bearing Strength (MPa)	Flexural Strength (MPa)
MIX_1	0.5516	30.218	4.755
MIX_2	0.5895	24.38	5.737
MIX_3	0.2413	14.101	—

diameter ratio of 1:10. Because of the loading system and the small thickness-to-external diameter ratio it was approximated with a thin ring, and as such the calculations are based on equations developed for thin rings [10]. Figure 3 shows typical failure of a FRC pipe in V-shaped three-edge bearing test. Cracks along four generating lines placed at the ends of two perpendicular diameters were noticed at failure.

Flexural Performance

FLEXURAL PERFORMANCE OF PIPES. Figure 9 and Table 2 present flexural behavior for FRC extruded pipes. MIX_1 and MIX_2 pipes were tested only. An overall look at the graphs indicates that performance in flexural strength for FRC extruded pipes containing silica fume and PVA fibers with or without latex is comparable. However, MIX_2 performs better than MIX_1, and its corresponding flexural strength is higher (17%).

The pipe was approximated with a beam working in flexure, and the calculations were performed according to the elementary theory of beams with annular cross section. Figure 4 shows typical failure of a FRC pipe in flexure. Cracks along two generating lines at the ends of

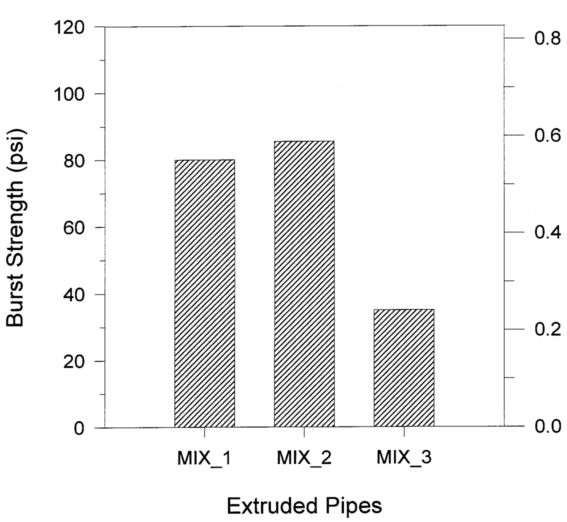

FIGURE 7. Hydrostatic burst strength for different extruded FRC pipes.

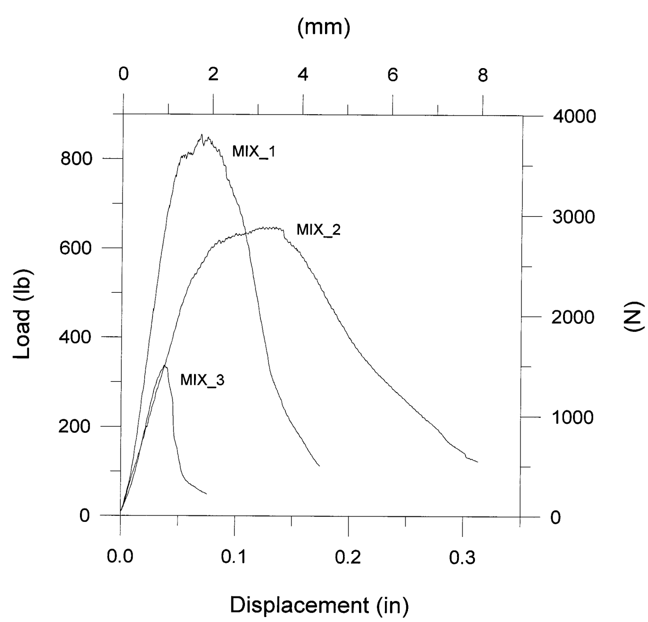

FIGURE 8. Load-displacement behavior from V-shaped three-edge bearing test for different extruded FRC pipes.

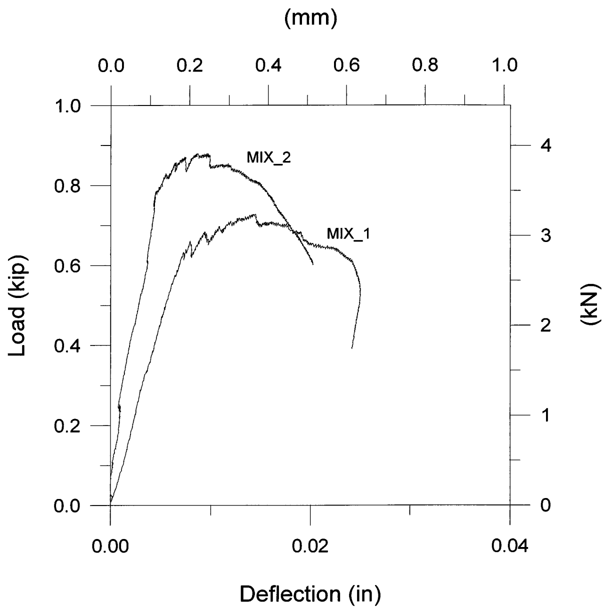

FIGURE 9. Flexural load-deflection curve for different extruded FRC pipes.

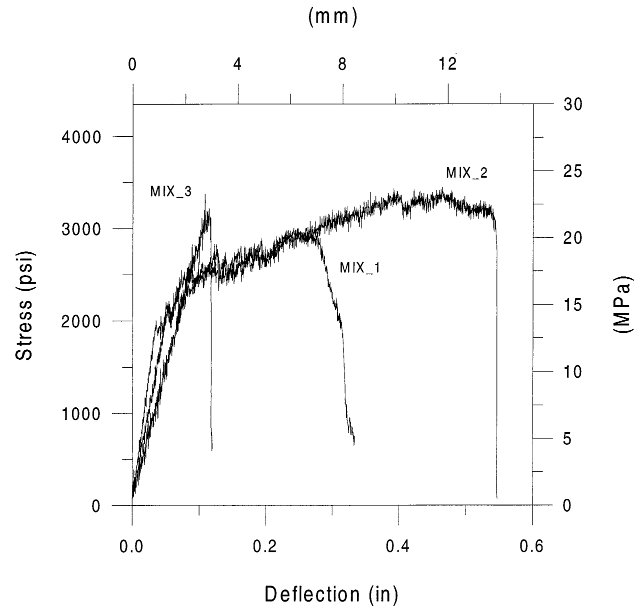

FIGURE 10. Flexural stress-deflection curve for different extruded FRC sheets.

a diameter normal to the loading plane were noticed at failure.

FLEXURAL PERFORMANCE OF SHEETS. Figure 10 and Tables 3 present flexural behavior for extruded FRC sheets. An overall look at the graphs indicates that the performance in flexural strength of extruded FRC sheets containing silica fume and PVA fibers with or without latex is better at failure than that of FRC sheets containing metakaolin and glass fibers. MIX_1 and MIX_2 show strain hardening behavior, whereas MIX_3 did not.

The specimens with glass fibers had somewhat higher stress at elastic limit (LOP) as compared to those made with PVA fibers. The maximum flexural stress was essentially similar for all three sets of specimens. The sheets made with PVA fibers and latex exhibited the most ductility; the deflection at the maximum flexural stress for these specimens was about four times as compared to that for the sheets reinforced with glass fibers.

It should be noted that the strain at failure is only approximate, as it was calculated based on the deflection at failure using equations valid for elastic materials. This is true only for linearly elastic materials. From the load-deflection curves it is quite clear that the behavior of extruded FRC sheets is nonlinear. In addition, once cracks are formed, strains are localized and not homogeneously distributed. As a result, calculated values of strains are dependent on the geometry of the specimen, as well as on the testing arrangement.

FRC extruded sheets containing silica fume and PVA fibers perform better and are more flexible than those containing metakaolin and glass fibers. MIX_2 shows 42.90% and 75% higher load-point deflection, respectively, than MIX_1 and MIX_3 (Table 3). Figure 5 presents typical composite flexibility of a FRC sheet in flexure.

Flexural modulus of elasticity (Table 3) was computed using two methods. In the first method the linear load-deflection curve up to the bend-over point was used. Since the load-deflection curve did not show a clear bend-over point in some cases, it was also decided to obtain modulus of elasticity values based on the curve up to one third of the maximum load. The values of modulus of elasticity obtained based on the load-deflection curve up to one third of the maximum load showed higher values for MIX_1 (20%) and comparable values for MIX_2 and MIX_3. The toughness of the

TABLE 3. Flexural test results of extruded FRC sheets

Test Series	MIX_1	MIX_2	MIX_3
Flexural strength (MPa)			
Elastic (LOP)	13.404	15.787	20.963
Failure (MOR)	21.771	23.816	22.167
Flexural strain (%)			
Elastic (LOP)	0.0682	0.0968	0.139
Failure (MOR)	0.4291	0.7379	0.1553
Load-point deflection (mm)			
Elastic (LOP)	1.03	1.492	2.606
Failure (MOR)	6.491	11.367	2.892
Modulus of elasticity (based on BOP) (MPa)	20.029	16.578	15.375
Flexural toughness (N-m)	0.475	0.809	0.082

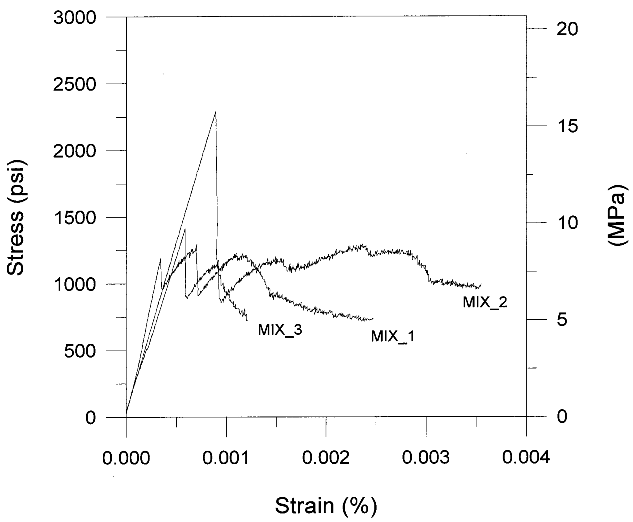

FIGURE 11. Tensile stress-strain curve for different extruded FRC sheets.

specimen (Table 3) was obtained based on the area under the load-deflection curve up to the point where the post-peak load reaches 5% of the maximum load. Extruded FRC sheets containing silica fume and PVA show much better performance in flexural toughness than those containing metakaolin and glass. Flexural toughness of MIX_2 is 41% and 90% higher, respectively, than those corresponding to MIX_1 and MIX_3, respectively.

Tensile Performance

Figure 11 and Table 4 present tensile behavior for extruded FRC sheets. Even though the tensile strength of MIX_3 is higher than that of MIX_1 and MIX_2 (73% and 56%, respectively), it shows a brittle behavior. Tensile strength for extruded FRC sheets containing silica fume and PVA is about 2.45 times lower than corresponding flexural strength, while that for the mix containing metakaolin and glass fibers is about 1.45 times lower.

Tensile strain at peak for MIX_1 and MIX_3 is about the same (Table 4). However, MIX_2 presents higher tensile strains (22% and 27% than MIX_1 and MIX_3, respectively).

TABLE 4. Tensile test results of extruded FRC sheets

Test Series	Tensile Strength (MPa)	Tensile Strain (%)	Modulus of Elasticity (GPa)
MIX_1	8.78	0.0931	21.950
MIX_2	9.775	0.1198	18.368
MIX_3	15.265	0.0869	17.117

Tensile modulus of elasticity was calculated using the stress-strain curve (Table 4). Although stress-strain curves present a linear behavior up to the peak load, the curve was limited up to a stress corresponding to one third of the maximum load. MIX_1 shows higher tensile modulus of elasticity (16% to 22%) than MIX_2 and MIX_3, which show comparable values. Flexural and tensile modulus of elasticity are comparable for all the FRC extruded test series.

The response of extruded pipe was not as good as that of the corresponding extruded sheet. Possible reasons for this are technological process, lack of sufficient dimensional uniformity of the pipe, and biaxial action (in case of the hydrostatic pressure test). This indicates that there are potentials for improving the pipe characteristics and match them with plate characteristics by improving the uniformity of the pipe. Even though MIX_3 showed higher tensile properties in sheet, the hydrostatic/burst strength of the pipe was low. This suggests that strain hardening behavior (ductility) plays a key role in improving the burst strength of pipe.

Summary and Conclusions

- Presence of silica sand helps improve the surface finish.
- Presence of latex increases the ductility of the composite.
- Refinement of die design and mixture ingredients and their proportions helped obtain better hydrostatic/burst characteristics and surface finish for the pipe.
- Extruded FRC cementitious composites containing silica fume and PVA fibers (MIX_1 and MIX_2) perform better than the one containing metakaolin and glass fibers (MIX_3).
- MIX_2 showed the best overall performance as well as in esthetic aspect, i.e., surface finish.
- MIX_3 exhibits poor behavior, which might be explained by either glass fibers breaking during the extrusion process or inefficiency of glass fibers in the extruded mix composition.
- Even though MIX_3 showed higher tensile strength for plates, the hydrostatic burst strength of pipe was significantly low. This indicated that the strain hardening behavior and increased ductility of the composition play a key role in influencing the hydrostatic burst strength of the pipe.
- Technological process needs to be improved to provide more dimensional uniformity.

Acknowledgments

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